3 Boiler Operation, Tube Failures by Erosion and Erosion-Oxidation and Remedial Measures for Tube Failures

3.1 Boiler Operation

3.1.1 Introduction

It is important to be familiar with the operation of a boiler and all its components before one can investigate measures to control boiler erosion. It is also important to know each part of the boiler so that one can better understand the research done by others. Most of the information in this section is adapted from Singer [**11**].

3.1.2 Boiler Operation in a Nutshell

Refer to Figure 3-1 for a schematic of a typical pulverized-coal-fired boiler during the following discussion. Boilers burn pulverized coal to generate heat. This heat is transferred to the walls of the boiler through radiation. The walls of the boiler consist of many vertical tubes through which water circulates. The heat it receives via radiation heats the water in the tubes and the water starts boiling. The steam and water in the tubes are separated in the steam drum. The separated steam is then returned to the boiler for superheating in the superheater tubes. The separated water is returned to the bottom of the boiler through downcomer tubes.

3.1.3 Boiler Components

3.1.3.1 The Furnace

Heat generated in the combustion process appears as furnace radiation. Water circulating through tubes that form the furnace wall lining absorbs a certain percentage of heat. Waterwalls consist of vertical tubes connected at the top and bottom to headers. These tubes receive their water supply from the steam drum by means of downcomer tubes connected between the bottom of the drum and the lower headers. The steam, along with a substantial quantity of water, is discharged from the top of the waterwall tubes into the upper waterwall headers and then passes through riser tubes to the boiler drum. In the boiler drum the steam is separated from the water. The water together with incoming feedwater, is returned to the waterwalls through the downcomer tubes.

3.1.3.2 Superheater Tubes

The purpose of the superheater is to raise the boiler steam temperature above the saturated temperature level. As the steam enters the superheater in an essentially dry condition, further absorption of heat increases the steam temperature. Superheaters designed for high temperatures and pressures require high-strength alloy tubing. This alloy must also have great oxidation resistance. High operating pressure means increased tube thickness. Thicker tubes are subjected to higher outside metal temperatures and are thus more subject to external corrosion.

3.1.3.3 Economisers

Economisers help to improve boiler efficiency by extracting heat from flue gases discharged from the final superheater section of a radiant unit. In the economiser, heat is transferred to the feedwater supplied to the boiler.

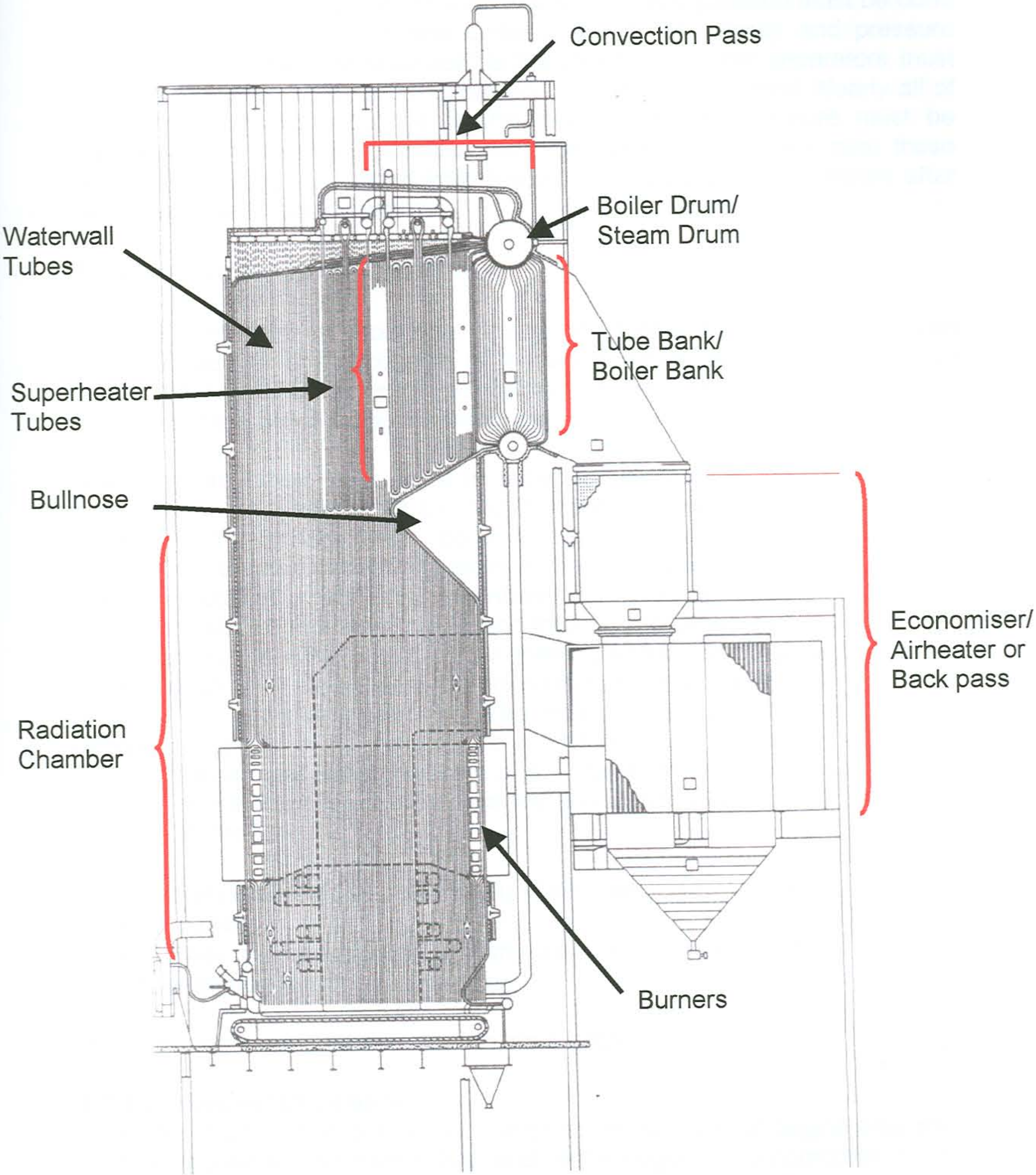

Figure 3-1 A Typical Pulverised-Coal-Fired Boiler [11]

3.1.3.4 Air-Heaters

Air heaters have two functions: they cool the gases before they pass to the atmosphere and at the same time they raise the temperature of the incoming air of combustion. The heating of the incoming air improves the efficiency of the boiler.

3.1.3.5 Steam Drum (Boiler Drum)

Before steam leaves the boiler and enters the superheater, practically all the boiler water must be separated from the steam. This separation must be done within a matter of seconds and under a variety of velocity and pressure conditions. The pressure drop across the steam and water separators must not be sufficient to affect boiler circulation or water-level control. Nearly all of the liquid and solid impurities in the steam and water mixture must be separated from the steam before use. The boiler drum serves both these factors: separating the steam from the water and purifying the steam after being separated from the water.

3.1.4 Water/Steam Circulation

The fact that water is circulating through the tubes of the boiler has been described above. The circulation of the water and steam will be discussed here in more detail because it is an integral part of boiler operation. The whole operation of the boiler is dependent on the circulation system of the boiler.

The term circulation, as applied to steam generators, is the movement of water, steam or a mixture of the two, through heated tubes. The tubes are situated in the furnace walls, boiler banks, economisers, superheaters or reheaters. Adequate circulation results in the cooling fluid absorbing heat from the tube metal at a rate which maintains the tube temperature at or below design conditions. In boilers, circulation through the varied systems of heated tubes can involve either just the flow entering and leaving the system (called once-through flow), or a means of recirculating the fluid, or some combination of these two circulation concepts. The most critical circulating system in a large boiler is that of the furnace walls. The walls are at the same time the area of highest heat absorption rate and a major structural component of the unit. There are three types of furnace wall circulation systems used for steam generation, they are:

- Thermally-induced circulation (natural circulation) with inherent recirculation.
- Thermally-induced circulation, pump-assisted, with recirculation.
- Once-through, with no recirculation.

These systems are now discussed in more detail.

3.1.4.1 Thermal Circulation

This type of circulation is at subcritical pressure. Circulation begins only after heat is applied to the riser tubes and, once begun, is proportional to the amount of heat locally supplied. To maintain the overall system pressure drop as low as possible, boilers using this principle for cooling the furnace enclosure need large flow areas in downcomers and supply tubes. Thermal circulation boilers can be used at any waterwall operating pressure below critical pressure, as long as there is some finite density difference between the water in the downcomers and the saturated steam-water mixture in the heated circuits.

3.1.4.2 Pump-Assisted Thermal Circulation

This type of subcritical boiler recirculation system uses an external mechanical force, produced by one or more low-pressure-differential pumps, located in the downtake system to supplement the thermal head. Pump-assisted thermal circulation units find particular application at the high subcritical pressure levels, where there is reduced fluid static head energy available to recirculate the furnace wall fluid. The only difference between thermal circulation and pump-assisted thermal circulation boilers is in the circulating systems. Both types share the same kind of firing methods, means of superheating and reheating and controlling superheater and reheater outlet temperatures.

3.1.4.3 Once-Through Circulation

In a once-through boiler, there is no recirculation of water within the unit. In elemental form the boiler is merely a length of tubing through which water is pumped. Heat is applied, and the water flowing through the tube is converted into steam. In actual practice, numerous small tubes arranged to provide effective heat transfer similar to the arrangement in drum-type boilers replace the single tube.

3.1.5 Fuel-Burning Systems

The ideal fuel-burning system would have some of the following characteristics:

- There must not be excess oxygen or unburned fuel after combustion.
- Low energy input necessary for ignition.
- Stable combustion over a wide range of conditions.

For combustion to take place with a stoichiometric quantity of air, infinite resident times at temperatures above the ignition point at which complete burnout of the combustibles takes place, would be necessary. There must thus be excess air during combustion. The less air necessary for complete combustion, the more efficient is the firing system.

The rate and degree of completion of a combustion process (chemical reaction), are greatly influenced by temperature, concentration, preparation and distribution of the reactants, by catalysts, and by mechanical turbulence. All these factors have one thing in common: to increase contacts between the molecules of the reactants. Higher temperature increases the velocity of molecular movement, with a resulting increase in frequency of contact between molecules. At a given pressure, three factors limit the temperature that can be attained to provide the greatest intermolecular contact. These are the heat absorbed by the combustion chamber enclosure, the heat absorbed by the reactants in bringing them to ignition temperature, and that absorbed by the nitrogen in the air used as a source of oxygen. The higher the concentration of a reactant, the higher is the opportunity for contact between interacting molecules.

There are basically three different configurations of fuel-firing systems: horizontally-fired, tangentially-fired and vertical-fired systems. The first two are the most common and they will be discussed in more detail.

3.1.5.1 Horizontally-Fired Systems

In this configuration of firing, the fuel is mixed with primary combustion air in individual burner registers. Adjustable inlet vanes impart a rotation to the preheated secondary air. The degree of air swirl, coupled with the flow-shaping contour of the burner throat, establishes a recirculation pattern extending several throat diameters into the furnace. The burners are located in rows, either on the front wall only, or they are on both the front and rear walls. The major part of combustion must take place in the recirculation zone. The rate of combustion drops off rapidly as the reactants leave the reaction zone. The air-fuel ratio must therefore be maintained within close tolerances.

3.1.5.2 Tangentially-Fired Systems

The fuel as well as the air is projected from the four corners of the furnace on a line tangent to a circle, lying in a horizontal plane, at the centre of the furnace. When a tangentially-fired system projects a stream of pulverised coal and air into a furnace, the turbulence and mixing that takes place along its path are low compared to horizontally-fired systems. This occurs because the turbulent zone does not continue for any great distance as the expanding gas soon forces a streamlined flow. As one stream impinges on another in the centre of the furnace during the intermediate stages of combustion, they create a high degree of turbulence for effective mixing.

3.1.6 Conclusion

The purpose of a pulverised–coal-fired boiler is to generate steam for industrial applications or power generation. Heat is transferred from the burning coal to the tubes through radiation. The tubes include waterwall tubes, superheater tubes, economiser tubes and boiler bank tubes. Water circulates through the tubes and steam is generated. There exist a few water circulation systems such as thermal-induced circulation and pump-assisted thermal-induced circulation. The steam and water are separated in the boiler drum. There also exist different fuel-burning configurations of which tangentially-fired and horizontally-fired systems are the most common. The boiler discussed in the rest of this dissertation uses thermal-induced circulation and has a horizontally-fired system.

3.2 Boiler Tube Failures

3.2.1 Introduction

Boiler tube failures constitute the major cause of lost availability in steam generating plants world-wide [**12**]. There is plenty of published research on boiler tube failures and on the philosophy of how to prevent these failures. The bulk of the published research covers fire-side tube failures but water-side failures are also dealt with in detail. This study will concentrate on fire-side boiler tube failure mechanisms and especially on impingement erosion. The causes of boiler tube failures are many and varied, as will become evident in the following discussion.

3.2.2 Repeat Failures

Repeat boiler tube failures are frequent, multiple failures with the same physical appearance, occurring in the same flow circuit or even the same tube and resulting from the same failure mechanism and root cause [**13**,**14**]. An alarming number of outbreaks of boiler tube failures are repeat failures [**13**].

Primary factors influencing repeat boiler tube failures are almost always one or more of the following [**13**,**14**]:

- Not following state-of-the-art operation, maintenance, or engineering practices; lack of proper tube failure analysis and root-cause verification.
- Wrong choice of long-term corrective/preventive action.
- Lack of definitive tube-failure reporting and continuous monitoring.

Without a proper understanding of the mechanism of failure, the root cause, and the appropriate corrective actions, it is not possible to apply permanent engineering solutions [**13**].

3.2.3 Mechanisms of Boiler Tube Failures

A mechanism of boiler tube failure is defined as the process which degrades the tube and produces a failure. Determining the correct mechanism of a boiler tube failure is important for the prevention of future tube failures. Proper corrective measures can be undertaken to alleviate the root cause or causes for a failure only when the correct mechanism is known [**15**].

Boiler tube failures can be classified into three broad categories, each forming part of the classic "bath tub curve" describing component reliability [**12**]. The three categories of failures are:

- Wear-out failures
- Failures due to faulty repairs
- Random failures

Wear-out failures are time-dependant failures that describe the natural tendency for the frequency of tube failures to increase as the boiler ages. Faulty repairs are generally the cause of failures due to shortcomings in quality control at breakdowns or overhauls. Random failures are independent of accumulated operation or starts, being instead the result of transient operational conditions or the development of faults during operation.

Jones[**16**] gives three major reasons for boiler tube failures, i.e.:

- Tube overheating
- Tubes that have been attacked chemically
- Tubes that are thinned down from the fire-side

Dimmer and Dooley[**14**], Mayer[**15**] and Dooley[**17**] give six broad classes of significant boiler tube failure mechanisms and possible reasons of failure:

- Stress rapture – Short-term overheating; high temperature creep
- Water-side corrosion - Hydrogen damage; oxygen pitting
- Fire-side corrosion - Low temperature; coal ash
- Erosion - Fly ash; falling slag; sootblower; coal particle
- Fatigue - Vibration; thermal; corrosion
- Lack of quality control - Maintenance cleaning damage; welding defects; material defects

Colannino[**18**] gives five major modes of fire-side tube failure:

- Ash-induced corrosion
- Reduced-atmosphere corrosion
- Dew-point corrosion
- Impingement erosion
- Stress-corrosion cracking

Each failure given by Colannino[**18**] will be discussed in more detail.

3.2.3.1 Ash-Induced Corrosion
Ash corrosion occurs in the high temperature parts of the boiler such as the superheater section. Under high temperatures, complex chemical reactions occur. The evidence of ash corrosion is metal thinning combined with a chemical analysis that identifies eutectic compounds. Low ash fusion temperatures indicate a potential for ash corrosion. A possible cure for ash corrosion is the operation of the superheater at lower temperatures.

3.2.3.2 Reducing Atmospheres
Corrosion of the waterwall can occur under reducing conditions. Pyrosulfate compounds volatilise at high temperatures, and thus is found in liquids and form only on cool surfaces such as waterwall tubes. The pyrosulfate compounds dissolve the protective oxide coating on the boiler tube. This type of corrosion acts preferentially on the crown of the waterwall boiler tube. The most cost-effective cure for this type of erosion is metal cladding with high-nickel alloys or thermally transparent refractories.

3.2.3.3 Dew-Point Corrosion
Dew-point corrosion can occur wherever metal temperatures are below the dew point of the flue gas. For flue gas containing only water and CO_2, metal

surfaces must be below 100°C. Not even the stack of a boiler is this cool. Thus, other compounds, most notably SO_3, can elevate the dew point to as high as 166°C. Metal components subject to attack by the corrosive dew are economisers and air preheaters. Dew-point corrosion is generally evidenced by smooth corrosion of metal parts. The cure to dew point corrosion is adequate washing to remove sulphur deposits that may cause localised dew-point corrosion.

3.2.3.4 Impingement Erosion

Impingement occurs preferentially where the flue gas is forced to rapidly change direction. Impingement removes the protective oxide layer that all high temperature surfaces must develop for oxidation resistance. As the old oxide layer is abraded, the metal re-oxidises, consuming the underlying metal. This phenomenon is also called erosion-corrosion, which will later be discussed in more detail. The metals exposed to impingement may have a sandblasted or shiny appearance or an undulating surface. The cure for impingement is to reduce the impact of abrasives with metal surfaces. This can be accomplished with changes in materials for the boiler tubes or by the use of deflecting plates or screens.

3.2.3.5 Stress-Corrosion Cracking

Stress-corrosion cracking occurs due to preferential chemical attack along regions of high stress. Chlorides and hydroxides are noteworthy agents for stress-corrosion cracking. Water, superheater and reheater tubes are most prone to attack by stress-corrosion cracking. Boiler tubes are under stress due to internal steam pressures. Stress-corrosion cracking is a microscopic phenomenon and is typically invisible to the naked eye.

3.2.4 Conclusion

All the different mechanisms of boiler tube failures have been discussed. It can be seen that the causes of boiler tube failures are indeed many and varied. What makes boiler tube failures even more complex is the fact that two or more of the above mentioned mechanisms can occur at the same time. In this study, however, boiler tube failures due to impingement erosion are very important and will be concentrated on in the following section.

3.3 Erosion

3.3.1 Introduction

The American Society for Testing and Materials (ANSI / ASTM G40) defines erosion as the *"progressive loss of original material from a solid surface due to the mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles."* [**19**]

There are two basic fields of published research on erosion. The first field is the effect of the particle and environmental characteristics, i.e. hardness, shape, size, velocity, angle of impact etc., on erosion. The second field of erosion research is the response of the target material to impinging particles.

The bulk of the literature covers erosion characteristics at room temperature. Some authors have observed that erosion behaves somewhat differently at higher temperatures. There are authors that performed research on erosion especially in simulated boiler environments [**20**,**21**,**22**,**23**,**24**,**25**].

High-temperature erosive wear is a serious problem in the coal-burning industry as it often leads to unscheduled and costly outages. The problem is especially severe in coal-fired power stations in Southern Africa as the coal has a high quartz content, some of which survives combustion to cause erosive wear damage on its path out of the boiler [**23**].

The wear rate may not be sufficiently high (with the exception of high-ash quartz-rich fuels) to cause tube failures during the first few years of operation, but the wear-damage occurs deep in the economiser and superheater tube banks where it can remain unnoticed [**26**].

3.3.2 Regions where Erosion Occur in a Boiler

Erosion tends to be localised in particular areas of the boiler, and particular parts of a given tube bank. Refer to Figure 3-1 for the tube bank location described in this section. Localisation of erosion by eddy flow around a weld bead on a tube is not uncommon [**27**]. Except for the localised effect of erosion in boilers, the properties of the ash that causes erosion are also important parameters that determine in which areas of a boiler erosion will occur. Erosion also occurs where the ash particles are flung against boiler walls due to inertial forces when the flow direction changes.

3.3.2.1 The Nature of Ash in Erosion Regions

The nature of the interaction of the ash with the boiler tubes changes from a tendency to form a deposit (captive) to one of erosion (non-captive) towards the cooler parts of the boiler [**23**,**26**,**28**]. Failures due to erosion usually occur in the cooler superheater – reheater regions, either towards the top of the furnace or in the back pass [**28**,**29**].

Erosion wear in pulverised-coal-fired boilers occurs chiefly in the economiser and the primary superheater and reheater sections ('the middle temperature ranges'). The flue gas temperature in these passages is below 1000K [**26**,**30**].

Two essential conditions for erosion must exist wear to take place in the middle-temperature heat-exchanger sections, namely [**26**]:

- Ash particles entrained in the flue gas below 1100K no longer have the propensity for formation of adhesive deposits, and the ash has acquired an erosion-wear property.
- The ash-particle impaction takes place at sufficiently high velocity to cause erosion-wear, leading to subsequent tube failures.

3.3.2.2 Waterwalls

One of the most common areas where fly-ash erosion of waterwall tubes is encountered is around the top of the rear wall of the furnace, where the flue gas is turned to flow through the rear pass [**27**].

3.3.2.3 Tubes

Blockage of the normal gas flow path by slag or ash deposits can result in channelling of the flue gas through the tube banks. Hence fouling can compound erosion problems. Various design features of tube banks can give rise to localised disruptions of the gas flow, and locally turbulent regions may result in associated erosion [**27**]. Some features in the layout of the primary superheaters and reheaters and in the economiser create high velocity zones where erosion usually takes place [**26**,**28**]. Other localities of high-velocity zones of the flue gas flow are created by the gaps between the deep horizontal tube banks and duct walls [**26**]. In the gaps, the lower resistance causes higher velocities [**31**]. Sites of erosion failure are located where local peak gas velocities occur. These are recognised to be very local (on the order of centimetres) and turbulent. The erosion rates at these areas of high velocities are assisted by the muldistribution of ash. Ash-based effects can be considered to be secondary to the peak velocity effects [**17**].

The erosion wear of superheater, reheater and economiser tubes is further enhanced by the tendency of large and erosive fly-ash particles to concentrate in the flue gas stream near the rear wall after the U-turn at the top of the combustion chamber [**26**].

3.3.3 Characteristics of Erosion

From numerous studies of erosion, it appears that the most important variables are what may be termed system variables, such as fly-ash particle velocity and angle of impingement, and operating variables resulting from the type of coal burned and the combustion conditions, which define the size, shape, density and hardness of the fly-ash particles [**27**].

The amount of erosion damage varies, depending on the combination of many factors. In fact, it is the combined effect of these factors that could make the difference between a tolerable erosion rate and a rapid erosion rate that leads quickly to tube failures. The most critical factor of erosion would have very little effect if other factors were not present to combine to create an erosive condition. The list of better known factors that cause erosion includes [**32**]:

- Particle velocity
- Particle density
- Angle of impingement
- Particle size and shape
- Fluid flow conditions
- Temperature
- Mechanical properties of particles
- Mechanical properties of the target material

In the erosion process, some of the above factors will have greater influence on the erosion rate than others, but all of them have to be taken into consideration in order to understand the mechanism of erosion.

3.3.3.1 Particle Characteristics

It is well documented that erosion rate is a strong function of the angle of attack, velocity, particle size, and particle and target materials.

3.3.3.1.1 Velocity of Impacting Particles

All researchers on erosion agree that the velocity of impacting particles is one of the most important parameters governing erosion wear. Erosion rates vary with particle velocity V according to the power law V^n, where n is on the order of two to four [**27**,**33**], but there is a critical velocity, below which no erosion damage will occur, assuming all other factors are held constant [**32**].

Early investigators of erosion proposed that the erosion process is proportional to the kinetic energy of the oncoming particles. This predicted relationship (i.e., $\varepsilon \sim V^2$) would almost be intuitively expected. Experimental research has however suggested that the velocity exponent is normally greater than two and this is perhaps the single most controversial issue in the study of erosion [**34**].

Table 3-1 contains a summary of research done on the velocity exponents of erosion.

Researcher and Source	Conditions of Study	Velocity Exponent
Grant and Tabakoff[34]	20° impact angle 90° impact angle	2.8 4
Shida and Fujikawa[24]	304 steel for temperatures of 300 and 650°C. Irregularly shaped silica particles were used as erodent.	2.8
Sun et al.[35]	Impact carbon steel, Cu by Al_2O_3, SiO_2 grains (30-40μm). Velocity range: 30-100m.s^{-1}.	2.01-2.69
Raask[26]	Carbon steel eroded by 75-125μm quartz sand. Velocity range: 20-30m.s^{-1}. 402°C.	2.5

Table 3-1 Summary of Research Done on Velocity Exponents of Erosion

Raask[26] presents a summary of work done by numerous researchers, all of which determined the velocity exponent between 2.0 and 2.9 for carbon steel target material.

This leaves one question: *What is the maximum velocity under which no erosion will occur for flue gas?*

The EPRI Report[27] states that typical design values for the average flue gas velocity range from about 20m.s^{-1} for low erosive coals, down to about 12m.s^{-1} for highly erosive coals. Raask[26] gives the maximum flue gas velocity for U.S. bituminous coals as contained in Table 3-2.

Type of ash	Weight fraction > 45 μm particles	Range of maximum velocities
Fine fly ash	0.15	12.2 – 19.1m.s^{-1}
Coarse fly ash	0.3	11.4 – 17.1m.s^{-1}
Exceptionally coarse ash	0.5	10.6 – 14.9m.s^{-1}

Table 3-2 Maximum Velocity of Fly Ashes for Various Bituminous Coals

3.3.3.1.2 Particle Impingement Angle

Together with particle velocity, one of the important parameters that affect material erosion is the angle of attack at which particles strike the target surface. Changes in the particle impact angle can have a marked influence on the erosion wear-velocity relationship i.e. the velocity exponent. Ductile and brittle materials also behave differently for different particle impingement angles.

Shida and Fujikawa[24] found the maximum erosion rate to be at impingement angles of about 20°-30° for ductile materials and normal impingement (90°) for brittle materials. Kratina et al.[32] stated that ductile materials are affected worst at about 30° impact angle, while hard, brittle materials show the greatest loss at a 90° angle of impact.

Work conducted by Grant and Tabakoff[**34**] is widely respected. The abrasives they used were alumina (Al_2O_3) and quartz (SiO_2). For all velocities tested, the angle of maximum weight loss occurs at an angle of approximately 20°. In another study, Tabakoff and Balan[**36**] found it to be between 20° and 25°. As the angle of attack increases from this value, the erosion reduces to a residual value at 90°. The normal component of velocity does not significantly contribute to ductile erosion. The kinetic energy of the particles is dissipated by plastic deformation of the target material without significant material removal [**34**].

Ninham[**37**] used angular quartz particles (70 – 200μm diameter) and silicon carbide particles (250μm average diameter) as erodents in tests to investigate the erosion behaviour of a number of alloys. It was found that the erosion response of high strength materials, particularly those eroded by quartz, is only weakly dependent upon impact angle. Most materials gave rise to a rather flat erosion vs. angle plot, with a peak at roughly 60° impact.

3.3.3.1.3 Particle Concentration

Erosion rate was found by Shida and Fujikawa[**24**] to be a linear function of the particle concentration in the concentration range between 30 and $120 g.m^{-3}$, tested at 300 and 650°C. The CEA Research Report[**31**] also states that erosion wear is in proportion to particle loading. This is true up to a point where the situation changes from erosion to abrasion of the surface. When the particle loading is large enough, some particles cannot strike the specimen due to the blanketing effect of other particles. Kratina et al.[**32**] also stated that erosion is a linear function of particle density.

3.3.3.1.4 Effect of Different Erodent Size

Research has shown that the particle size does not influence erosion after a certain threshold value is reached. This threshold value is dependent upon both particle velocity and particle size [**26**,**32**,**34**]. Tilly and Sage[**38**] found the plateau to be reached at 45μm for quartz particles and that erosion increases continuously for brittle materials. Raask[**26**], on the other hand, stated that impacting quartz particles smaller than 5μm have little effect on erosion. Fan et al.[**39**] concluded that smaller particles led to a larger value of the velocity exponent than larger particles. It was observed by Tabakoff et al.[**40**] that the erosion damage caused by coal ash particles is much lower owing to their smaller size than compared with erosion damage caused by alumina and quartz particles.

3.3.3.1.5 Effect of Different Erodent Shape

The geometric shape of particles will determine the erosion mechanism involved. Sharp-edged grains are likely to remove material by a cutting action, while spherical grains will cause the most damage by cracking the surface at a 90° impact [**32**]. The role of microcutting is recognised to be significant in case of sharp particles while ploughing occurs in the case of round particles [**41**].

3.3.3.1.6 The Effect of Temperature

The erosion behaviour at 300 and 650 °C does not seem to differ significantly from that obtained at room temperature [**24**]. Kratina et al.[**32**] state that the effect of temperature on erosion rate is less than one might expect.

3.3.3.2 Target Material Characteristics

Surface hardness, modulus of elasticity and scaling stress will invariably affect erosion. They combine to give the material its resistance to abrasion and impact erosion. They also determine the mode or mechanism of erosion involved [**32**].

<u>Erosion behaviour to different heat treatments and materials:</u>

- Brittle and ductile target materials exhibit different mechanisms of erosion [**42**].
- Erosion rate decreases with increasing tempering temperature [**36**,**43**].
- Erosion decreases with increasing spheroidisation [**43**].
- Erosion decreases with increasing proportion of bainite in the bainite-martensite structure obtained by austempering [**43**].

Whereas different heat treatments produce large changes in the mechanical properties, the erosion variation is comparatively small. In general, erosion rate increases with increasing hardness and the ultimate strength, but decreases with increasing ductility [**43**]. The ageing or work-hardening treatments carried out by Ninham[**37**] on the high temperature alloys had essentially no effect on erosion rates.

3.3.3.3 Hidden Factors Contributing to Erosion

There are hidden factors contributing to boiler erosion that can explain why in past cases two identical boilers in the same station experienced completely opposite erosion patterns. These hidden factors include [**32**]:

- Operational load
- Coal properties
- Operation time

These factors affect the gas flow and ash load in the boiler which, in terms of erosion investigation, can be translated into particle velocity and abrasive load.

3.3.4 Conclusion

Boiler tube failures due to erosion occur only in certain areas of a boiler. The properties of the ash particles and high particle velocity are to blame for the high erosion propensity in certain areas. It can also be seen that particle as well as target material characteristics are important factors influencing erosion rate.

3.4 Erosion-Oxidation

3.4.1 Introduction

Fly-ash erosion of primary superheater tubes, reheater tubes in the back pass, waterwall tubes and economiser tubes, is presently a more serious problem than fire-side corrosion [**27**]. It is nevertheless important to know what erosion-oxidation is and what the mechanisms of this phenomenon are.

Describing the phenomenon of erosion-oxidation in a way that makes use of the full breadth of understanding gained from studies of each phenomenon operating separately, is particularly difficult and challenging, because of the generally complex nature of both processes and the many potential combinations of the two phenomena [**44**].

3.4.2 Erosion-Oxidation Regimes

According to Wright et al.[**44**] there are three broad but distinct regimes of possible erosion-oxidation, which may overlap:

- Erosion dominates
- Erosion-oxidation interactions
- Oxidation dominates

These regimes are now discussed in more detail.

3.4.2.1 Erosion Dominates

The rate of oxidation is so slow that oxide removal makes a negligible contribution to the overall material loss, which occurs predominantly by the removal of metal. The presence of an oxide film may modify the erosion-oxidation interaction by changing the physical (for instance, coefficient of friction) or mechanical (for instance hardness) properties of the eroding surface. This regime will be encountered at low temperatures and, for very oxidation-resistant alloys, under conditions of very aggressive erosion where the erosive component completely overwhelms the contribution from oxidation.

3.4.2.2 Erosion-Oxidation Interactions

There are obviously several scenarios whereby interactions between erosion and oxidation can result, depending on the relative rates of oxide growth and the severity of the erosive action. In some circumstances, parts of the erodent particles may become detached and embedded in the target surface. The net result of the erosion-oxidation process in this regime is that the rate of oxidation increases as the scale is thinned locally. The magnitude of the increased oxidation rate depends on the thickness of oxide removed by the erosive impact.

3.4.2.3 Oxidation Dominates

The erosive component removes only the outer part of a continuous and growing oxide scale and effectively reduces the oxide thickness, thereby leading to a more rapid rate of oxidation than expected. This behaviour may be termed "erosion-accelerated oxidation".

3.4.3 Two Basic Regimes

Rishel et al.[**21**] give only two basic regimes of erosion-oxidation, namely erosion-enhanced oxidation and oxidation-affected erosion.

Erosion-enhanced oxidation occurs where the erosive process interacts with the scale and reduces its rate of thickening, thus promoting higher oxidation rates. Oxidation-affected erosion occurs when the metal surface is deformed by the erosive flux and oxide is removed very rapidly. This prevents the continuous oxide layer from forming on the surface of the metal.

3.4.4 Major Factors that Effect Erosion-Oxidation

Wright et al.[**45**] give a summary of factors that influence the simultaneous action of high temperature oxidation and erosion. The rest of this section is adapted from the paper of Wright et al.[**45**].

3.4.4.1 Effect of Metal Temperature

Even though a change in the gas temperature may or may not materially increase the erosion component, the overall contribution to material loss from erosion-oxidation can be significantly affected by a change in the oxidation (gas or metal) temperature.

3.4.4.2 Particle Size Dependence

In erosion-oxidation, in order for damage to occur, the erodent particle need not have sufficient energy to cut or abrade the metal surface but merely needs to cause the surface oxide to spall, which may require a considerably lower level of kinetic energy. Spallation is the mode of coating failure usually caused by internal stresses. Under these conditions, a change in particle size can have two effects:

- At fixed solids loading, an increase in the particle size leads to a decrease in the frequency of erosion events, hence to an increase in the time interval between erosion events.
- Larger particles imply a higher level of kinetic energy, hence the area over which spallation of the oxide scale occurs may be larger.

Therefore, a strong dependence on the erodent particle size is expected under erosion-oxidation conditions where the major loss is by oxide scale exfoliation. It is expected that the erosion-oxidation rates will increase with increased particle size.

3.4.4.3 Velocity Dependence

It would be expected that increasing the velocity at a given particle size and loading in the gas stream would result in an increase in the frequency of impacts, hence a decrease in the time interval available for oxidation to occur. Thus the overall rate of erosion-oxidation would be expected to increase with increasing velocity.

3.4.4.4 Impingement Angle Dependence

At a given solids loading in the gas stream, the effect of changing the angle of incidence of the erodent onto the alloy target is to alter the effective erodent flux experienced by the target surface. The erosion-oxidation rates will therefore decrease with decreasing angle of impingement.

3.4.5 Erosion-Oxidation of Carbon Steel in the Convection Section of a Boiler

Xie and Walsh[**46**] did some research on the erosion-oxidation behaviour of steels in the convection section of a boiler. It was found that erosion was slowest at the lowest metal temperature, regardless of the oxygen concentration, and slow under strongly oxidising conditions at high temperature and high oxygen concentration. Erosion was most rapid at high temperature in the presence of low oxygen concentration. At low oxygen concentration or temperature, erosion was dominated by the ductile behaviour of the metal, but, as conditions were made more oxidising by increasing oxygen concentration or temperature, the steady thickness of oxide scale and the influence of oxide on the erosion behaviour increased. The oxide was more resistant to erosion than the metal over most of the range of temperatures investigated. Therefore, the transition from metal-to-oxide controlled erosion, with increasing temperature, was accompanied by a decrease in the erosion rate.

3.4.6 Conclusion

This discussion of erosion-oxidation scenarios has suggested why the rate of material loss under such conditions is likely to be significantly greater than for erosion alone, since most of the material loss will be the result of the shedding of oxide scale rather than by the cutting or abrasion of the actual metal surface. The particle kinetic energy required to cause this form of material loss is likely to be lower than that required for metal loss by erosion alone.

3.5 Corrective Action Against Boiler Erosion

3.5.1 Introduction

The operating conditions in a coal-fired power station are conducive to fireside corrosion and erosion, both in the furnace wall and in the superheater and reheater areas, and these effects cause tube wall thinning and premature failure. The problems do not occur uniformly, however, and are concentrated locally within a boiler. Corrosion is influenced by coal quality and combustion conditions. Erosion is even more localised in its effect, and results from dust and ash entrainment in the gas stream. [**47**,**48**]

Traditionally, power utilities used temporary maintenance procedures (like pad welding and tube shields) to remedy fly-ash erosion in fossil-fuel-fired boilers. The EPRI report [**27**] illustrates that reliable, permanent solutions to these problems, though initially costly, may prove more economical in the long run.

Remedial measures for alleviating erosion-wear damage of the superheater, reheater, and economiser tubes by continuous impacting of the flue-gas-borne ash are not easily found [**26**].

3.5.2 Basic Courses of Action for Reducing Fly-Ash Erosion in Boilers

There are basically five courses of action available for reducing fly-ash erosion in any location in a boiler [**27**].

- Reduce the bulk velocity in the boiler. (Achieved by lower excess air levels, reduced operating load and lower levels of hot gas recycle.)
- Even out the gas flow across the boiler section to remove turbulent regions. (Achieved by the use of baffles.)
- Minimise the number of impacts of fly-ash on the tubes by reducing the loading of fly-ash in the gas. (Achieved by washing the coal [**49**].)
- Even out the concentration of fly-ash across the boiler section by eliminating centrifugal stratification. (Can be achieved by baffling.)
- Decrease the erosivity of the fly-ash. (Can be achieved by changing the fineness of the coal.)

3.5.3 Different Remedial Measures

Remedial measures used by utilities to combat fireside erosion include both sacrificial and flow-modification approaches. Sacrificial methods involve a range of approaches, including the use of shields, wear plates, deflectors, coatings, and increased tube wall thickness, but essentially treat only the symptoms of the problem. Flow-modification methods attempt to deal with one of the causes of the problem, and entail the use of hardware (e.g. deflectors, perforated plate, or expanded-metal screens) that reduces local fluid velocities in the regions where erosion is occurring. This approach is considered to have the potential to provide a permanent solution to the problem [**27**]. The CEA

Research Report[**31**] states that the prevention of high local velocities is the best way of preventing localised erosion problems.

Table 3-3 and Table 3-4 obtained from different sources give some remedial measures for boiler tube failures due to fly-ash erosion.

Measure	Effect on erosion	Comment
Decrease of ash content of coal	Could have a significant effect as a result of reduced dust burden and less-abrasive ash	May not be practicable and will increase the cost of fuel
Improved soot blowing	Enhances heat transfer; reduces temperature and velocity of the flue gas; prevents deposit blockages of velocity peaks	Improves the heat transfer and hence the performance of the boiler; Sootblowers may cause erosion by themselves
Removal of ash from superheater and economiser hoppers	Prevents re-entrainment of coarse and abrasive ash from fuel hoppers	Many boilers do not have hoppers
Reduction of combustion air preheat temperature	Would reduce the temperature and hence the velocity of flue gas	Would reduce slagging and corrosion, but may increase the unburned carbon in ash
Baffles for high velocity gaps	Can significantly reduce localised erosion wear	Should be applied as soon as the erosion-wear pattern becomes evident
Application of weld layers, shields, and plasma-sprayed coatings	Will extend the life of tube when erosion wear is localised	Should be applied before the damage becomes extensive

Table 3-3 Different Remedial Measures for Boiler Tube Failures [26]

Location	Symptoms	Causes	Temporary Measures	Recommended Long-Term Measures
• Leading edges of all tubes • All pendant superheater/reheater surfaces especially bottom bends at exit from furnace nose to rear pass • Roof and back wall • At top of rear pass • Rear pass superheater/reheater and economiser, tube bends (all rows) adjacent to back wall of rear pass • Tube rows adjacent to side walls of rear pass • With finned tubes, at base of fins • Near tube bank stiffeners • Tubes immediately after open areas in tube bank • Adjacent to soot-blower runs	• Polishing of leading surfaces of tubes • Smoothing of weld beads • Obvious flattening of leading edges or sides of tubes • Cutting of tube supports where local gas jetting might be expected • Flattened areas of tubes with longitudinal cracks • Thin-edged (longitudinal ductile failure if rate of erosion is rapid)	• Overall (bulk) flue gas velocity too high • Local gas velocity too high due to blockage or plugging, or design faults • Local turbulence • Misalignments of tubes (maintenance) • Plugging of flow passages • Very high fly-ash loading in flue gas • Stratification of fly-ash • Unusually erosive fly-ash • Malfunctioning of soot-blowers (poor alignment, insufficient maintenance) • Use of excessive pressure with sootblowers	• Reduce bulk velocity by operating at reduced load • Padweld or shield damaged areas and monitor closely • Replace tubes and monitor closely • Encase critical areas in refractory	• Blend or wash coal to decrease ash loading • Reduce flue gas velocity by reducing excess air • Reduce flue gas velocity by redesigning tube bank • Remove tubes • Increase spacing between tubes • Eliminate tube fins • Install flow control screens • Install baffles at entrance to back pass to redistribute fly-ash • Institute detailed tube thickness monitoring and remaining life calculations • Improve maintenance of sootblowers • Set proper operating procedures for sootblowers

Table 3-4 Remedial Measures for Fly-Ash Erosion of Superheater, Reheater and Economiser Tubes [27]

3.5.3.1 Sacrificial Remedial Measures

3.5.3.1.1 Coatings

The high cost and long lead-time in obtaining special tubes, coupled with the incidental costs of tube replacement, make the application of the surface coatings with specific properties an attractive proposition [**47**]. Care must be taken, however, because in some instances the usage of coatings is ineffective [**50**].

The materials used as coatings need to be effectively protected against corrosion and erosion. They must have a high thermal conductivity in order to provide a good service behaviour and effective and economic maintenance layout [**51**].

Coatings are not viewed with enthusiasm by some utilities, because of the experience of poor performance of coatings applied by faulty techniques [**27**]. One of the most important parameters when applying coatings, is the spray angle, or angle of incidence of the spray material on the substrate. Site spraying is further complicated by the closeness of the tubes in the boiler [**47**]. Care is required so that any heat treatments to cure or harden the coatings do not affect the base material properties [**29**].

It is important to know what influence the coating has on the heat transfer of boiler tubes. Nguyen[**52**] tested the heat transfer characteristics of three different coatings: ceramic coating, black plasma coating and a metallic coating. The ceramic coating and black coating transferred more heat than a bare tube whilst the metallic coating transferred less heat than a bare tube.

Levy and Wang[**53**] determined that small grain size, low porosity and the absence of cracks were the microstructural features that enhanced erosion resistance of coatings. Hardness levels and composition have a secondary effect on coating performance.

3.5.3.1.2 Shields

Because the areas where erosion occur are associated with high-velocity, turbulent gas flow, the proper fixturing of shields is important. Shields which are too large, misaligned, or which can move out of position, and fixturing which further disturbs the gas flow, can lead to an enhancement of the erosion problem [**27**]. Stainless-steel erosion shields give some protection to the plain carbon-steel tube, but care must be taken to shield the whole damaged area [**29**].

3.5.3.1.3 Pad-Welding

Pad-welding should be discouraged, since it is one of the causes of a large number of repeated failures [**27**], due to:

- insufficient material remaining in the tube wall,
- dissimilar metal effects, and
- copper embrittlement.

Pad-welding should not be considered a permanent fix, but should only be used in an emergency situation to extend tube life until the next scheduled outage for maintenance [**17**,**27**].

3.5.3.1.4 Alternative Materials

Where corrosion rates are high, the need for frequent replacement of tubes can be reduced by the use of a higher grade material with improved corrosion resistance, or, in the case of erosion, wrappers may be used [**47**]. Boiler tubes can be manufactured from materials specially designed for erosive/corrosive boiler application [**50**,**54**,**55**].

3.5.3.2 Flow-Modification Approaches

The basic cause of boiler tube failure is that the flue gas velocity is too high for the ash erosion wear propensity of given fuel supply, and once the boiler plant is built, the velocity of flue gas flow in erosion-affecting passages cannot be greatly reduced. There are, however, some measures that should be considered for reducing the overall velocity of the flue gas and eliminating the high velocity zones where the ash impaction erosion occur [**26**]. The second basic cause of fly-ash erosion, where flow-modifying approaches can be used to reduce erosion, is particle concentration [**49**].

3.5.3.2.1 Flow-Modifying Screens and Baffles

Expanded-metal screens are installed in order to control erosion by modifying the flow velocity, reducing excessive gas velocities and redistributing the ash load. As already mentioned, the erosion of a metal surface by a particle-laden flow is influenced by the physical properties of the fly-ash particles and the metal, particle impact angle and the incident particle speed. Erosion is linked to one of these factors and a predominance of any one of these factors leads to an increase in the erosion potential. Thus the control of the carrier gas velocity is important. Due to the boiler geometry, flows with skewed velocity distributions develop and this leads to high velocities and channelling in sections of the boiler. This channelled flow contains a higher concentration of fly-ash leading to erosion problems in those areas. The erosion can be controlled by modifying the flow within the boiler through the use of screens, particularly in the critical areas of high gas velocity [**56**]. Refer to Figure 3-2 for an example of screen location.

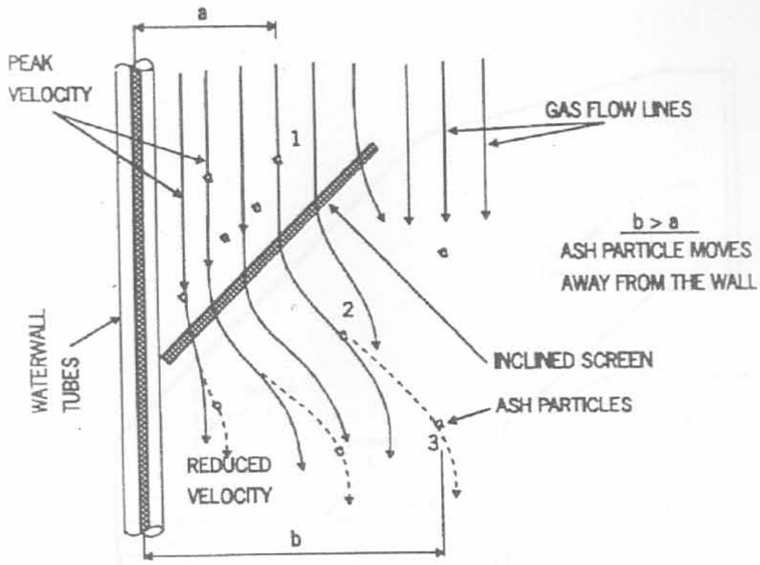

Figure 3-2 Schematic Showing of Expected Screen Behaviour [56]

Typically, screens are used to modify fluid flow by creating or eliminating large-scale velocity or pressure non-uniformities and for the production or for the reduction of turbulence. The placement of the screen requires knowledge of flow turning and the redistributing capabilities of the screen.

The installation of horizontal baffle plates are used to block open areas and reduce non-uniform gas flow. The use of totally solid baffles can cause movement of the erosion to an adjacent area, thus expanded stainless wire meshes would be preferable. Care must be taken to ensure that the local high velocity is not transferred to other locations [**29**].

Baffles intended to effectively prevent gas flow between the tube banks and to the walls have sometimes acted to deflect and concentrate a stream of fly-ash onto adjacent tubes, with the result that highly-localised wastage has been experienced. Such secondary effects can be minimised if sufficient clearance can be maintained between the baffles and the downstream tube bank so that jets and eddies induced by the baffles are dissipated ahead of the tubes. Baffle plates containing holes (punched plate) to allow some gas flow, and so reduce the deflection/concentration effect, are also used but have introduced a new problem. Depending on the positioning of these baffles with respect to the downstream tubes and the resistance to flow imposed by the plate, flow through the holes may result in concentration of the fly-ash and accelerated erosion of the first tubes to intersect the gas flow downstream [**27**].

3.5.3.2.2 Flow Modification in Boiler Back Pass

Figure 3-3 shows the positions of screens intended to minimise economiser erosion in the boiler back pass [**27**]. The gap between the tube bundles can be seen in the detailed view of Section A-A in Figure 3-3. Figure 3-4 shows the application of the screen over the gap in the centre of the economiser in Figure 3-3.

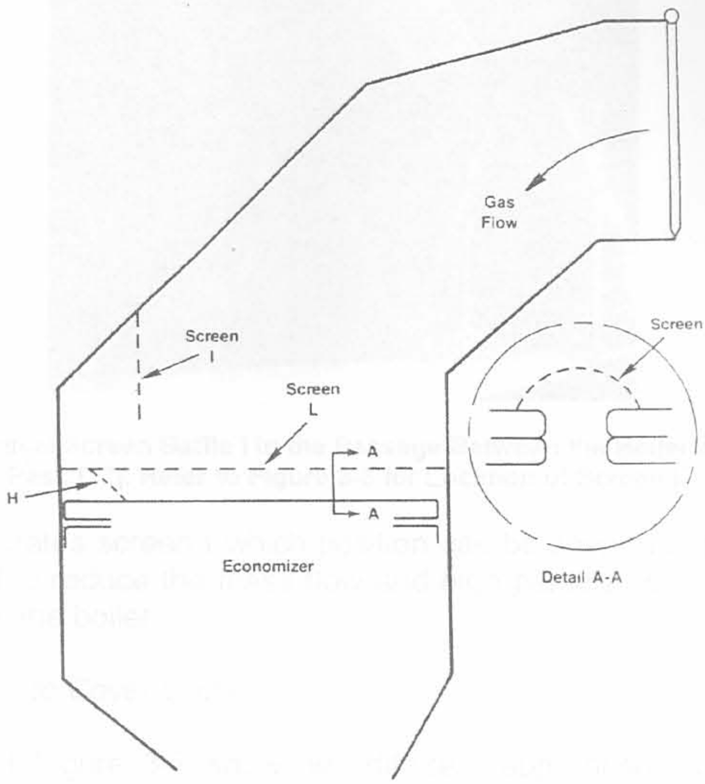

Figure 3-3 Boiler Geometry for Economiser Section – Fly-Ash Erosion Protection through the use of Screens[27]

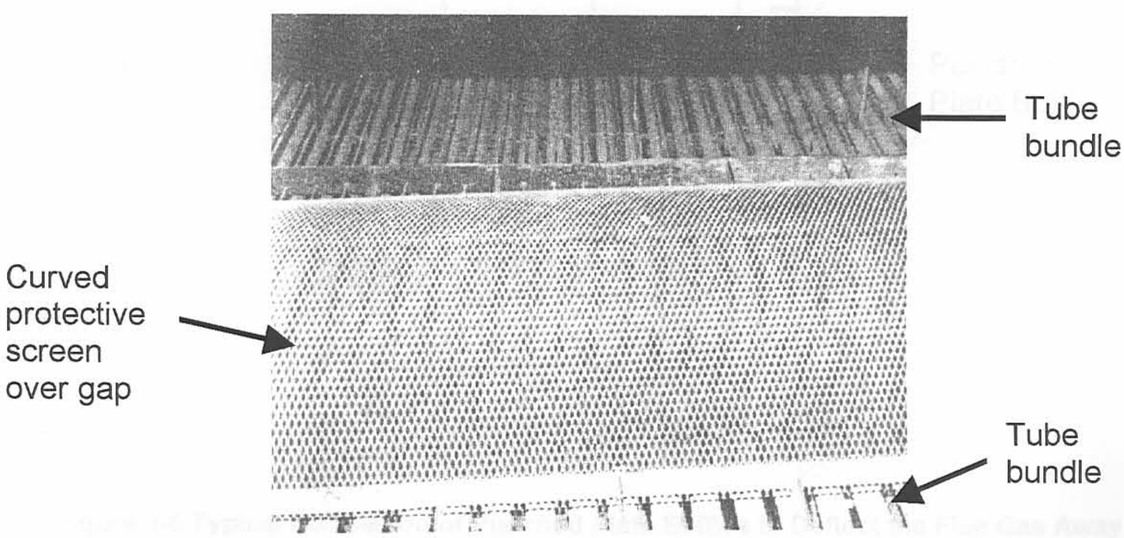

Figure 3-4 Protective Screen L Over the Gap Between Tube Bundles in the Centre of the Economiser [27]. Refer to Figure 3-3 for Location of Screen L

The screen is curved to provide a variable resistance and as such the high velocity and ash are redistributed to obtain a uniform velocity and a uniform ash concentration [**32**].

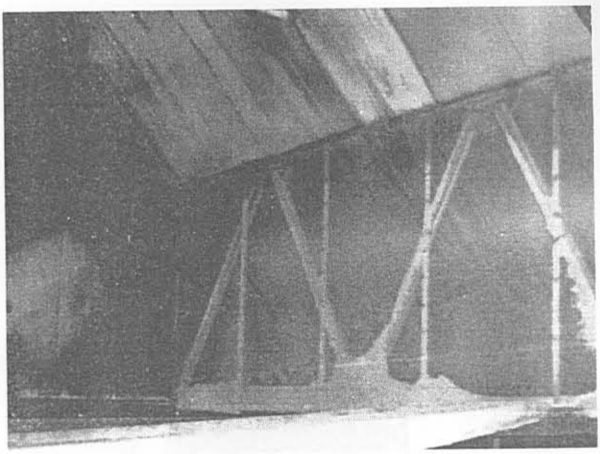

Figure 3-5 Vertical Screen Baffle I in the Passage Between the Boiler and the Back Pass [27]. Refer to Figure 3-3 for Location of Screen I

Figure 3-5 illustrates screen I which position can be seen in Figure 3-3. This screen is used to reduce the mass flow and high particle concentration near the back wall of the boiler.

3.5.3.2.3 Baffles to Cover Gaps

Figure 3-6 and Figure 3-7 show two different applications to cover gaps between tube banks and boiler walls.

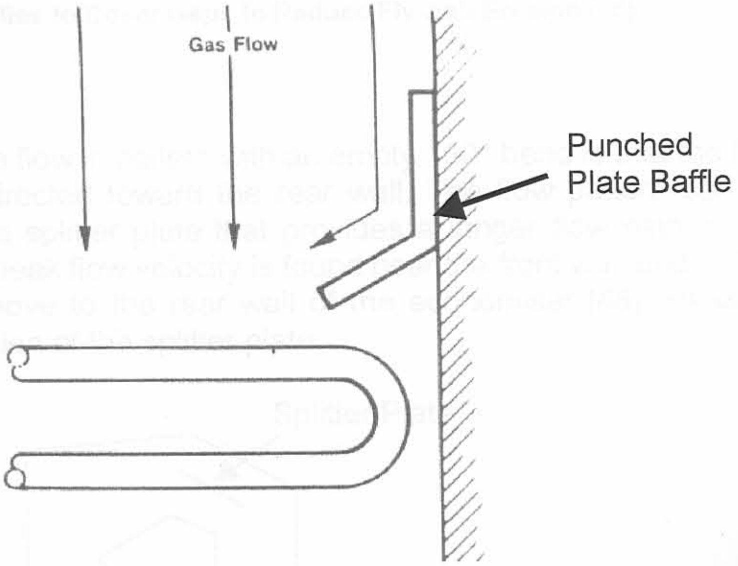

Figure 3-6 Typical Installation of Punched Plate Baffles to Deflect the Flue Gas Away from the Gap Between the Tube Bank and Boiler Wall [27]

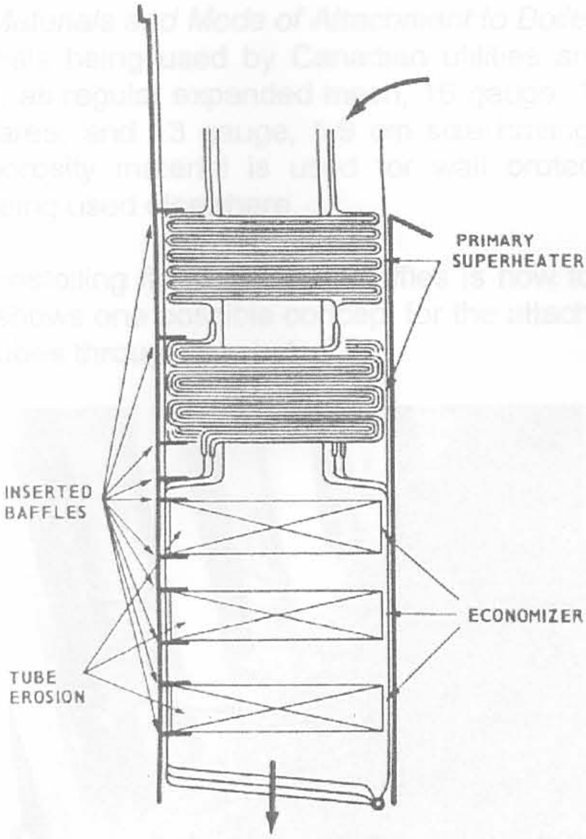

Figure 3-7 Baffles to Cover Gaps to Reduce Fly-Ash Erosion [26]

3.5.3.2.4 Splitter Plate

The main feature of the flow in boilers with an empty 180° bend is that the flue gas and fly-ash are directed toward the rear wall. The flow pattern can be modified by inserting a splitter plate that provides a longer flow path at the bend. In this case the peak flow velocity is found near the front wall and not all the fly-ash particles move to the rear wall of the economiser [**48**]. Refer to Figure 3-8 for the location of the splitter plate.

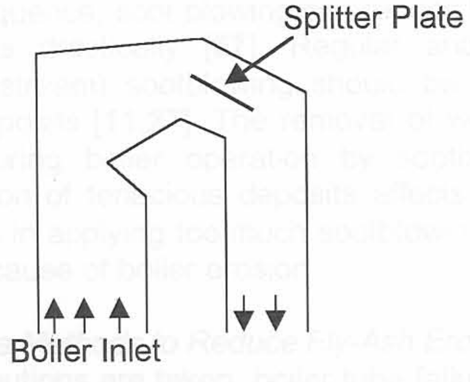

Figure 3-8 Splitter Plate to Defelect Flow in the Upper Part of a Boiler[48]

3.5.3.2.5 Screen Materials and Mode of Attachment to Boiler Tubes

The screen materials being used by Canadian utilities are stainless steels, typically Type 304, as regular expanded mesh, 16 gauge, 1.3 cm size having 47 percent open area, and 13 gauge, 1.9 cm size having 75 percent open area. The high porosity material is used for wall protection, with the 47 percent material being used elsewhere.

A predicament of installing flow-modifying baffles is how to attach them in a boiler. Figure 3-9 shows one possible concept for the attachment of protective screens to boiler tubes through brackets.

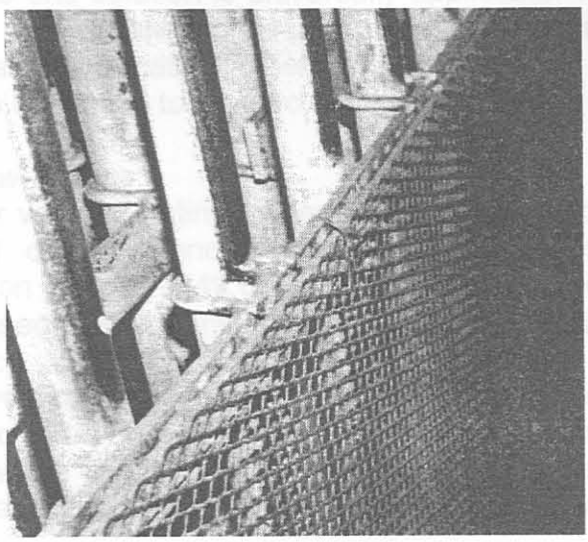

Figure 3-9 Mode of Attachment for Protective Screen through the use of Brackets[27]

Care must be taken when applying flow-modifying screens, because when screens are applied wrongly they can cause severe erosion. Erosion can be inflicted on the tubes where they are attached to the screens [**49**].

3.5.3.3 Other Remedial Methods

3.5.3.3.1 Sootblowing

If used in the right sequence, soot blowing can reduce boiler tube erosion and plant operating costs drastically [**57**]. Regular and properly sequenced (upstream and downstream) sootblowing should be capable of preventing plugging by loose deposits [**11**,**27**]. The removal of weakly bonded deposits can be achieved during boiler operation by sootblowing. However, the extensive accumulation of tenacious deposits affects boiler availability [**58**]. Care should be taken in applying too much sootblowing because sootblowing can itself be a major cause of boiler erosion.

3.5.3.3.2 Maintenance Methods to Reduce Fly-Ash Erosion

No matter what precautions are taken, boiler tube failures are going to occur. However, the service life of boiler tubing can be extended through proper maintenance and care [**16**].

Many authors propose maintenance visions to prevent boiler tube failures [**12**,**13**,**14**,**15**,**16**,**17**,**18**,**57**,**59**,**60**,**61**,**62**,**63**,**64**]. These visions include new management and maintenance plans to reduce boiler tube failures as well as expert systems to predict boiler tube failures and boiler tube life.

Accurate prediction of the lives of boiler tubes is difficult because of uncertainties associated with loading conditions, erosion/corrosion rates, geometry of the eroded/corroded areas, and material properties [**64**].

Techniques and strategies employed to overcome tube degradation are many and varied, and no one solution is universally applicable. Where decay rates are low it is often most economic simply to replace the worn tube with new material of similar specification when routine surveys indicate that the effective thickness has fallen to a particular level [**47**].

3.5.3.3.3 Cold Flow Studies

The use of cold air velocity testing to identify turbulent velocity areas, followed by installation of diffusing and distribution screens, provide permanent solutions for erosion problems [**49**,**65**]. The great advantage of this technique is that it can be used after the installation of the flow modification devices to test their efficiency. Velocity readings must be taken on a large-scale grid across various levels of the boiler as was done by Black and McQuay[**66**] and the CEA Research Report[**67**], and on a fine grid in areas where high velocities are known or expected to be present [**27**]. This technique has been applied very successfully to many boiler units in a number of countries [**17**].

The results of the research done by MacDonald[**67**] confirms the usefulness of cold air velocity testing in abatement of erosion and boiler tube failures. The results indicate a major requirement for cold flow tests to detect local flow conditions. The measurement of cold air flows is the most important task and the most critical variable in erosion control programs.

Drennen et al.[**68**] summarised a program to control and prevent boiler tube failures from fly-ash erosion. The heart of the program is the cold air velocity test in the boiler. The program is used to identify the type and placement of flow control devices that redistribute ash and gas to reduce the erosion potential. Refer to Figure 3-10 for a road map of activities for the control and prevention of fly-ash erosion through the usage of cold air velocity testing.

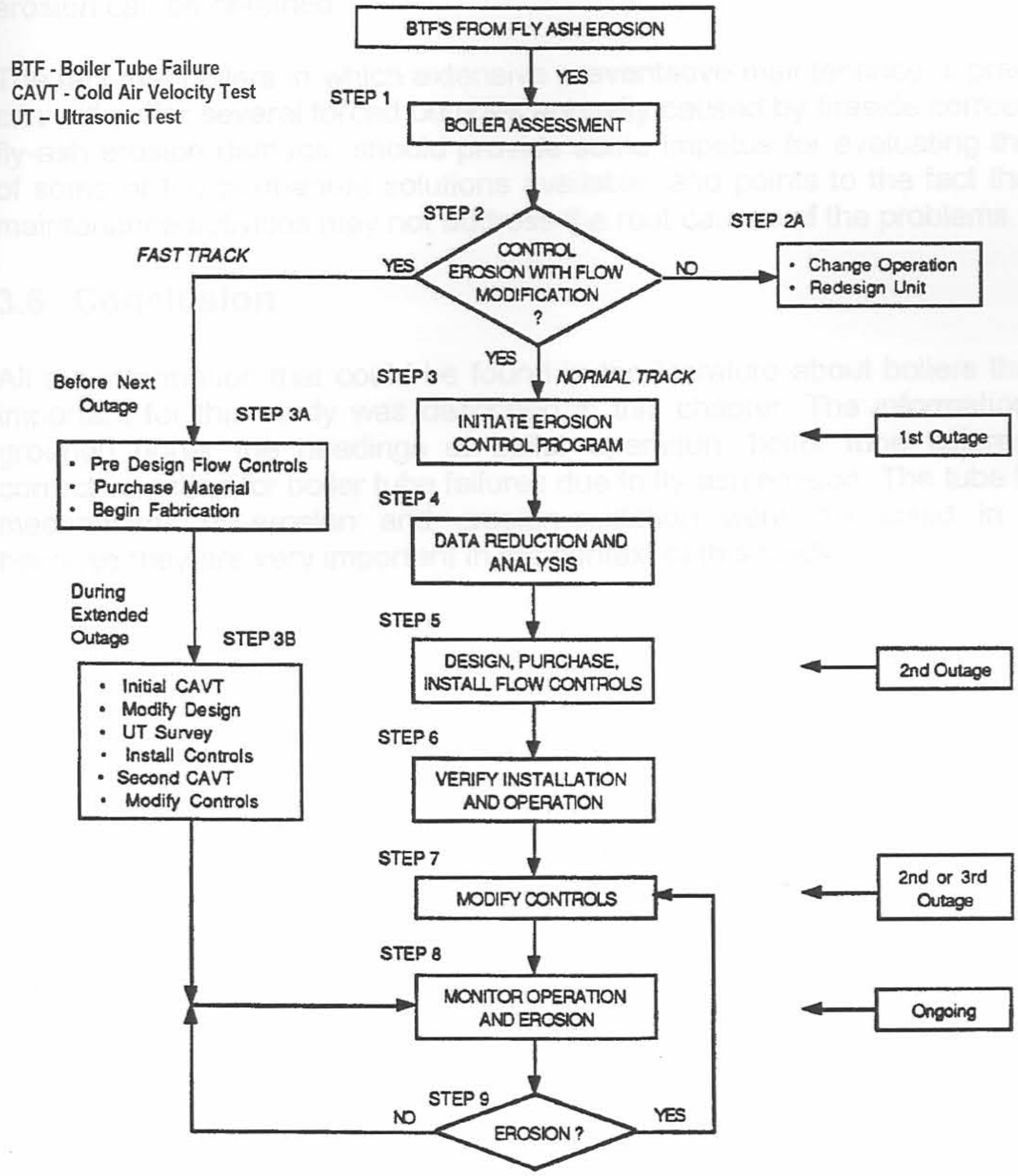

Figure 3-10 Road Map of Activities for Control and Prevention of Fly-Ash Erosion [68]

3.5.4 Conclusion

There are basically two different fields of approaches for corrective action of fly-ash erosion in pulverised-coal-fired boilers. These fields of corrective action are either sacrificial approaches or flow-modifying approaches. Sacrificial approaches include the usage of coatings, shields, pad-welding or the use of more suitable alternative materials. These corrective approaches essentially treat only the symptoms of the problem and do not provide permanent solutions. Flow modification approaches usually provide more permanent solutions, through the use of screens and baffles. The aim of flow-modification approaches is to redistribute the ash load and to prevent channelling of the flue gas. Through the use of cold flow studies together with the use of flow-modification approaches, permanent solutions to fly-ash erosion can be obtained.

The fact that boilers in which extensive preventative maintenance is practised can still suffer several forced outages annually caused by fireside corrosion or fly-ash erosion damage, should provide some impetus for evaluating the use of some of the permanent solutions available, and points to the fact that the maintenance activities may not address the root causes of the problems.

3.6 Conclusion

All the information that could be found in the literature about boilers that are important for this study was described in this chapter. The information was grouped under the headings of boiler operation, boiler tube failures and corrective action for boiler tube failures due to fly-ash erosion. The tube failure mechanisms of erosion and erosion-oxidation were discussed in detail because they are very important in the context of this study.